



Technical Report No. 32-156

**Objectives of the Mariner Venus
Microwave Radiometer
Experiment**

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA**

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PREFACE

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The *Mariner* Venus mission referred to in this report is a forerunner of the present *Mariner R* mission. The microwave radiometer experiment on the *Mariner R* mission scans the disc of the planet at only two frequencies — 13.5 and 19 mm.

ABSTRACT

At present, there are several models involving the surface, atmosphere (and ionosphere), and cloud conditions of the planet Venus which attempt to account for the observed high brightness temperature of 600°K in the microwave temperature region. None of these models can be definitely accepted or rejected on the basis of presently available data, and it is the goal of the microwave radiometer experiment planned for the *Mariner* Venus mission to determine which of the proposed models most nearly approximates Venusian conditions. The disc of the planet will be scanned at 4 wavelengths—4, 8, 13.5 and 19 mm—to measure the temperature distribution across the planet. Measurement accuracy is expected to be to within 2%. In addition to the study of gross thermal characteristics of surface and atmosphere (or ionosphere), some information regarding the fine-scale thermal variations will be obtained.

I. SUMMARY

Since Venus appears to be continuously covered by clouds, it is obvious that only in the microwave region can one be sure of penetrating clear to the solid surface. Because of the absorbing characteristics of the Earth's atmosphere, and because of the relatively poor resolution obtainable in this region of the spectrum, one is forced to utilize the platform afforded by a planetary flyby or orbiter in order to conduct a reliable high resolution study of the planet. To do so from Earth (neglecting terrestrial atmospheric attenuation) would require colossal radio telescopes or interferometric systems, both of which would require an almost impossible degree of mechanical precision, environmental control, etc. In contrast to this, a modest space probe antenna system can study planet surface features having diameters of 100 miles or so.

Over the past few conjunctions (1956–1959), measurements in the microwave region of the brightness temperature of Venus have indicated values of T_b ranging from about 315°K at 8 mm to about 600°K for wavelengths longer than 3 cm. At present, there are several models which present planet surface, atmospheric, and ionospheric conditions and which can explain the observed data. A microwave radiometer operating at 4, 8, 13.5, and 19 mm scanning the planet at close range can distinguish between these models and establish which one most closely approximates actual planet conditions. In addition to the obvious scientific value of such an experiment, the definite establishment of one model is of importance insofar as the future study of the planet is concerned.

II. INTRODUCTION

Within the last four years the possibility of performing astronomical experiments with equipment not confined to the surface of the Earth—particularly experiments not limited by the absorbing properties of the terrestrial atmosphere—rapidly changed to a probability and is now a reality. It is not surprising that the first such experiments were concerned with conditions in the immediate neighborhood of the Earth; and it is not surprising that the “second generation” experiments are directed toward increasing our knowledge of the Moon and nearby planets. Man has been studying the planets since the beginning of astronomical observations, yet many of the most fundamental properties of the planets have not been determined. This is a direct consequence of the fact that, except for Mars and Mercury, we are unable to observe the surfaces of the planets even with the most modern equipment. For example, Venus, the Earth’s so-called sister planet, has a cloud cover or layer so complete that no reliable observations of its surface have ever been made, and its rotation period, the orientation of its rotational axis, the nature of its surface and similar properties are all unknown at the present time. This report describes a microwave experiment which can be carried on a space probe to the vicinity of Venus and which is designed to provide information about the planet that is currently unobtainable utilizing ground-based experiments and present techniques. A review of our knowledge of Venus as it pertains to this experiment is presented; various interpretations of recent radio astronomical data are discussed; and the experiment and its objectives are discussed in detail.

Prior to 1956 our knowledge of Venus was limited to information which could be gained by studying the intensity, spectral distribution, and polarization of reflected solar energy and the infrared radiation emitted by the molecular constituents of its atmosphere. For our purposes, the most important results of these studies were: (1) CO_2 is one of the most if not the most abundant molecules in the atmosphere above the cloud layer, (2) the radiation temperature in the 8- to 14-micron band is 240°K (Ref. 1, 2), and (3) the rotational temperature of the 7820 and 8689 Å bands of CO_2 is 285°K (Ref. 3). It is not possible to fix the exact height of the effective emitting regions to correlate with these temperature determinations, but there is little doubt that they refer to regions at, or slightly below, the cloud layer, and it is generally felt that these temperatures are not representative of the surface of the planet.

Beginning with measurements made at the Naval Research Laboratory in 1956, and continuing since that time, microwave radiation has been detected from Venus, thus opening a new region of the electromagnetic spectrum for planetary studies. The first measurements, made at 3- and 10-cm wavelengths, when interpreted in terms of thermal radiation gave an equivalent black-body temperature of about 575°K , independent of wavelength. Subsequent measurements at these wavelengths have substantiated the early results, but observations at 0.8 cm have yielded temperatures considerably lower, about 350°K . All the measurements reported to the present time are shown in Table 1.

Table 1. Summary of radio observations of Venus

λ , cm	T_b , $^\circ\text{K}$	Date of observations	Reference
21	630 ± 130	March 8-10, 13, 1961	4
12.5	590 ± 200	March-May 1961	5
10.2	600 ± 65	September 17-October 10, 1959	6
9.4	580 ± 160	June 24, July 27, 1956	7, 8
3.75	573 ± 28		*
3.4	575 ± 60	February 12-March 5, 1958	6
3.37	575 ± 58	April 18, 19, 1958	9, 10
3.15	560 ± 73	May 5-June 23, 1956	7, 8
0.86	410 ± 160	January 29, February 5, 6, 11, 1958	11
0.80	315 ± 70	September 18, 1959	12
0.4	390 ± 120		13
0.4	352 ± 50		**

*Private communication from F. D. Drake.

**Private communication from C. R. Grant.

The striking contrast between the infrared and microwave temperatures can only be explained by (1) the radiation originating at quite different levels in the two cases and/or (2) the radiation originating by a non-thermal mechanism having a spectral distribution independent of wavelength, at least over the range from 3 to 10 cm. While it is possible that a nonthermal mechanism with suitable parameters, such as electron energy distribution, magnetic field, electron density, etc., could be invoked to represent the observations, the physical conditions required appear to be unrealistic (Ref. 14). For this reason, efforts to explain and interpret the Venus observational data have been mainly concerned with the

first alternative above—a spatial separation between the infrared and microwave emitting layers. Perhaps the most obvious explanation of the observed temperature discrepancy is that the microwave radiation originates at or very near the surface, while the infrared temperatures refer to the atmosphere near the cloud layer. The lower temperatures obtained at the shorter microwave wavelengths would then be due to absorption by the cooler atmosphere between the surface and the clouds (Ref. 15). It should be pointed out, however, that an alternative explanation is possible. The radio temperatures can be reproduced by considering instead a dense ionosphere at an electron temperature of about 600°K. This model is attractive in that it does not require such a high surface temperature but, instead, unusually high electron densities (Ref. 16–18). Both models are currently considered possible and will be discussed in detail below.

Since the discovery of radio radiation from Venus it has been recognized that a variation might be detected in the radio brightness temperature with the variation in phase of the planet as viewed from the Earth. Such a variation would be of extreme value in interpreting the results in terms of conditions on the planet or in its atmosphere. The difficulty in measurements of this sort—the necessity of absolute accuracy—is one which characterizes most measurements in radio astronomy. However, several researchers made observations during the 1959 inferior conjunction of Venus which were sufficiently accurate to give the first definite indication of the phase variation. The results, presented in Table 2, include only those cases where more than one observation was made by a group. Individual measurements, made by different observers, are not included. Once again, the contrast with the infrared results is large, because no appreciable temperature difference was detected at infrared wavelengths between the light and dark portions of Venus, thus implying that no phase variation is present. These measurements and their implications will be discussed in detail below.

With this brief review of some of the problems that confront the planetary astronomer as he considers Venus, it is obvious that more detailed measurements at a number of wavelengths, both longer and shorter than the presently available results, are needed to resolve some of the problems. With this in mind, it is planned to place several microwave radiometers in the *Mariner* probe to Venus to give information about the critical portion of the spectrum from 3 to 4 mm to 2 or 3 cm, the prime objective being to attempt to locate the source of microwave radiation. Measurements of this sort will give information that is unobtainable from ground-based

Table 2. Radio brightness temperature vs phase angle

λ , cm	T_b , °K	Phase angle, deg	Year	Reference
10.2	535 ± 60	214	1959	6
	675 ± 60	245		
3.75	563 ± 17	111	1959	•
	571 ± 17	121		
	581 ± 25	131		
	573 ± 28	165		
	616 ± 25	232		
3.4	520 ± 60	212	1958	6
	635 ± 60	241		
0.80	$315 \pm 30^{**}$	216	1959	12
	$335 \pm 36^{**}$	231		
	$355 \pm 90^{**}$	261		
	$440 \pm 90^{**}$	271		

*Private communication from F. D. Drake.

**Errors given here show the internal consistency of the results and can be used for relative comparisons. Absolute errors, which include systematic antenna errors, are a factor of 2.33 higher.

measurements at the present time. The reasons for this are twofold: (1) the Earth's atmosphere is largely opaque over most of the spectrum for wavelengths shorter than 1.5 cm, thus necessitating measurements made above the atmosphere; (2) it is impossible to study detailed areas of the planet from ground-based installations because the antenna required to obtain this angular resolution would be prohibitively large. Coupled with (2) above is the fact that the received signal is usually of the same order of magnitude as the noise power inherent in the receiver; thus accurate measurement of the received power is difficult, a fact which is reflected in the uncertainties of the entries of Table 1. These experimental shortcomings can be overcome by conducting the experiments from a probe passing close to the planet.

Finally, it should be pointed out that the problem of pinpointing the origin of the microwave radiation has more than just scientific or academic interest. The design of future Venus probes and their communication systems will depend to a great extent on where the radiation originates. If the surface temperature is actually near 600°K, the probe and its equipment must be designed to withstand temperatures of this order; on the other hand, if the radiation originates in a dense ionosphere it appears that communication with the probe after its passage through the ionosphere on its journey to the surface

would have to be done at mm wavelengths. This latter possibility would require much equipment which presently does not exist. Thus it is of the utmost importance for future experiments to learn where the radiation originates and as much as possible about conditions in the

atmosphere and on the surface. In the following sections the proposed experiment is discussed in terms of current theories together with the nature of the information to be gained and its impact on planning future experiments of a similar and/or more sophisticated nature.

III. PROPOSED MODELS

A. High Surface Temperature

After the discovery and confirmation of microwave radiation from Venus characteristic of temperatures of 575°K, a question was raised as to whether this temperature was the surface temperature of the planet and, if so, what that implied about the planet's atmosphere. Further work in this area was stimulated by the first positive detection of water vapor in the atmosphere of Venus as a result of high-altitude balloon observations.¹ It is well known that H₂O plays a vital role in the terrestrial atmosphere in determining the average temperature of the Earth, and it is natural to inquire whether a similar role is not possible in the Cytherean atmosphere.

The first problem to consider is this: On the basis of radiation theory, the known constituents of the atmosphere, the average insolation, and the absorbing properties of the atmospheric molecules, can a surface temperature of about 600°K be maintained with reasonable molecular abundances? This problem has been considered in some detail by Sagan, who considers the answer to be in the affirmative (Ref. 14). The method by which this important question may be answered is outlined as follows: Because of the conservation of energy, the absorbed incident solar energy must equal that radiated by the planetary surface plus that radiated by the atmosphere. If T_a is an average temperature of the atmospheric radiating layers, T_s is the surface temperature, and α is the absorptivity of the atmosphere, then

$$T_r^4 = \alpha T_a^4 + (1 - \alpha) T_s^4 \quad (1)$$

where T_r is the radiation temperature representative of the incident solar energy. The quantity T_r can be calculated with a fair degree of confidence by considering the insolation at the average distance of Venus from the Sun and including the effects of a finite albedo. Using an albedo of 0.68, $T_r = 350^\circ\text{K}$ if Venus rotates in synchronism with its period of revolution about the Sun, and $T_r = 250^\circ\text{K}$ for a rapidly rotating planet. Both of these determinations apply to a planet without an atmosphere. With $T_s = 600^\circ\text{K}$, Eq. (1) can be used to define limits on acceptable values of α because T_a must lie between 0°K and T_r . If T_a exceeded T_r , α would exceed unity, which is impossible. Thus it is found that $1 \geq \alpha > 0.884$

for a synchronously rotating planet, and $1 \geq \alpha > 0.971$ for a rapidly rotating planet.

These limits, which apply, of course, to the integrated absorptivity over the entire electromagnetic spectrum, are useful in determining an upper limit to the wavelength of complete atmospheric absorption. If it is assumed that the atmosphere is opaque for all wavelengths less than λ_c , then λ_c is determined from the above limits by the equation

$$\int_0^{\lambda_c} B_\lambda(T_s) d\lambda = (1 - \alpha) \sigma T_s^4 \quad (2)$$

where $B_\lambda(T_s)$ is the Planck radiation law, and σ is the Stefan-Boltzmann constant. Naturally, this method assumes that the surface radiates as a black body. Numerical integration of this equation shows that for $\alpha = 0.884$ complete absorption for all wavelengths less than 13μ is required, and for $\alpha = 0.971$ complete absorption must occur for all wavelengths less than 23μ . Sagan regards these numbers as being indicative of the presence of H₂O in the Cytherean atmosphere, because CO₂ cannot give complete opacity out to 23μ , and no common molecules have vibration-rotation bands in this region. However, pure rotation bands of asymmetric top molecules may be expected in this region, and H₂O is the most common example of an asymmetric rotor.

Fortunately, CO₂ and H₂O are among the most thoroughly studied molecules, and an abundance of data is available on their infrared spectra and emissivities. From such data—largely empirical—and Eq. (1), Sagan is able to calculate the amount of H₂O needed in the atmosphere of Venus to give the required "greenhouse" effect and to explain the 600°K surface temperature of the planet. Representative results of this calculation are shown in Table 3. By way of comparison, the same procedure may be applied to the terrestrial atmosphere, where an immediate check is available with the observed value. The theoretical computation gives 0.6 gm/cm² at the equator, which agrees favorably with the observed mean abundance of about 1 gm/cm². Thus, on the basis of Sagan's work, at least as much H₂O can be expected in the Cytherean atmosphere as in the terrestrial atmosphere and possibly considerably more.

¹Private communication from J. Strong.

Table 3. Theoretical values of H₂O in Venus atmosphere

	Nonsynchronous rotation	Synchronous rotation
Albedo	0.68	0.68
T _r , °K	250	350
α	0.994	0.902
H ₂ O, g/cm ²	9	1.5

One check on the applicability of Sagan's work to Venus is available. It is possible to calculate the expected abundance of H₂O above the cloud layer and compare this result with the value observed experimentally (Ref. 18). Typical computed values are given in Table 4, and these may be compared with the observed value of 1.9×10^{-3} gm/cm². Thus it is seen that the observed value seems to favor the case of Venus rotating synchronously, but an alternative could be found by invoking any mechanism, such as photodissociation, which would reduce the abundance of H₂O above the clouds.

Table 4. Theoretical values of H₂O above cloud layer

H ₂ O above surface, g/cm ²	Temperature of cloud layer, °K	H ₂ O above clouds, g/cm ²
1	220	2.4×10^{-3}
3	225	4.5×10^{-3}
10	233	1.2×10^{-2}

In summarizing, it can be said that the 600°K temperature of Venus indicated by the radio results can be characteristic of the surface if the H₂O abundance is comparable with or an order of magnitude greater than the value on Earth. It should be emphasized that little can be said about the properties of the atmosphere or the nature of the surface, because Sagan's results are insensitive to changes in the CO₂ abundance on Venus by an order of magnitude and variations in the surface temperature T_s at least as great as 100°K. However, as will be discussed below, it may be possible to set limits on both these important quantities from theoretical consideration of the existing radio data.

Having concluded that the surface temperature can be 600°K without requiring prohibitively large quantities of H₂O, the next question to consider is whether the substantially lower radio temperatures at 0.8 cm wavelength compared to those at 3 cm and 10 cm can be due to

atmospheric absorption and, if so, what does it imply about the Cytherean atmosphere? This question has been considered in detail previously for a particular set of model atmospheres (Ref. 19), and a summary of the method and results will be presented here. In general, the problem is attacked by assuming a model atmosphere based on as much experimental evidence as possible and then calculating the integrated microwave absorption and emission in the atmosphere. From this, the expected radio spectra of the planet and its atmosphere may be computed and compared with observations of Table 1.

The model atmosphere chosen for these calculations is as follows:

1. The atmosphere consists of 75% CO₂, 22%–25% N₂, and 0–3% H₂O. This is consistent with the observations that Venus's atmosphere is largely made up of CO₂. The N₂ abundance is higher than usually assumed, but the final results are not sensitive to the N₂ content.
2. The atmosphere is assumed to be in adiabatic equilibrium beneath the cloud layer and in isothermal equilibrium above the cloud layer. These are standard meteorological assumptions and reasonably approximate the terrestrial atmosphere. In addition, observations of Venus indicate that the atmosphere above the clouds is in approximate isothermal equilibrium.
3. The abundance ratios in (1) above are assumed to be uniform throughout the atmosphere. No data are available for a more sophisticated model, and the preliminary calculations do not warrant inclusion of varying mixing ratios.
4. The surface temperature is assumed to be 580°K, in agreement with the radio observations, and the temperature above the clouds is assumed to be 285°K, in agreement with the temperature obtained from the CO₂ measurements. This latter temperature is compatible with the radiometric infrared measurements if allowance is made for the reflectivity (Ref. 20).

With the preceding assumptions, the meteorological and microwave properties of the atmosphere are largely determined. In particular, the average adiabatic temperature gradient is determined to be 9.0°K/km; the scale height in the isothermal region is 6.86 km; the height of the cloud level is predicted to be at 33 km; and the pressure at the cloud level is 0.038 of the surface

pressure. These conclusions follow from the thermodynamic relations of adiabatic and isothermal equilibrium and the thermal properties of the assumed atmospheric constituents. The variation of temperature and pressure with height are shown in Fig. 1.

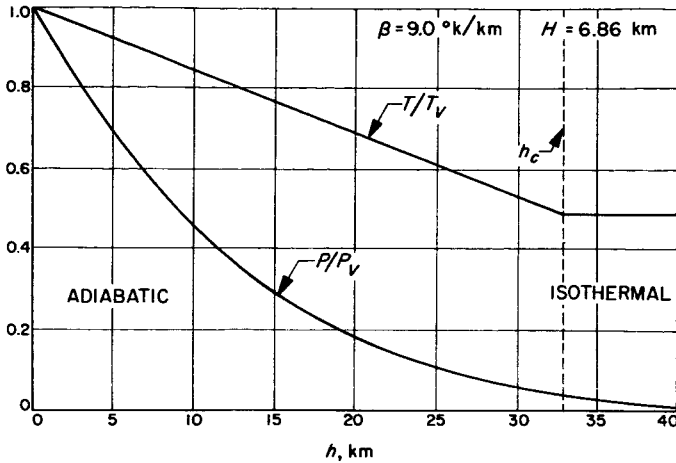


Fig. 1. The variation of temperature and pressure with height from the surface of Venus, assuming an atmosphere of 75 % CO_2 , 25 % N_2 ; the values are normalized to unity at the surface

The microwave properties of gases—in particular, CO_2 and H_2O —have been the subject of experimental investigation; consequently the microwave absorption and emission in the Cytherean model atmosphere can be computed with considerable confidence. The absorption coefficients, absorption per cm, of CO_2 and H_2O are given by (Ref. 21, 22)

$$\alpha_{\text{CO}_2} = \alpha_0' \frac{\nu^2 p^2}{T^{3.7}} \text{ cm}^{-1} \quad (3)$$

$$\alpha_{\text{H}_2\text{O}} = \frac{N \epsilon \nu^2}{T} \sum_i S_i \quad (4)$$

$$\times \left(\frac{\Delta \nu}{(\nu - \nu_{0i})^2 + \Delta \nu^2} + \frac{\Delta \nu}{(\nu + \nu_{0i})^2 + \Delta \nu^2} \right) \text{ cm}^{-1}$$

where ν is the frequency in cps, T is the temperature in $^\circ\text{K}$, p is the pressure in dynes/cm², N is the number of molecules per cm³, ϵ is the percentage of H_2O , $\Delta \nu$ is the line width parameter in cps, ν_{0i} are the H_2O resonant frequencies, and S_i and α_0 are constants relating to the molecular properties of H_2O and CO_2 . There is no interaction between the N_2 molecules and microwave energy.

The theoretical radio brightness temperature can be calculated once the total absorption in the atmosphere

is known. This can be obtained by integrating the absorption throughout the atmosphere after making suitable allowances for the variation of T and p with height in Eq. (3) and (4). Since the line-broadening mechanism is that of pressure broadening, the line widths $\Delta \nu$ are functions of T and p also. The optical depth, or opacity, τ , from the surface of the planet can be computed from the expression

$$\tau = \int_0^\infty (\alpha_{\text{CO}_2} + \alpha_{\text{H}_2\text{O}}) dh \quad (5)$$

where h is the height above the surface. The results are shown for a particular value of the surface pressure in Fig. 2. The resonance peaks are due to the H_2O lines

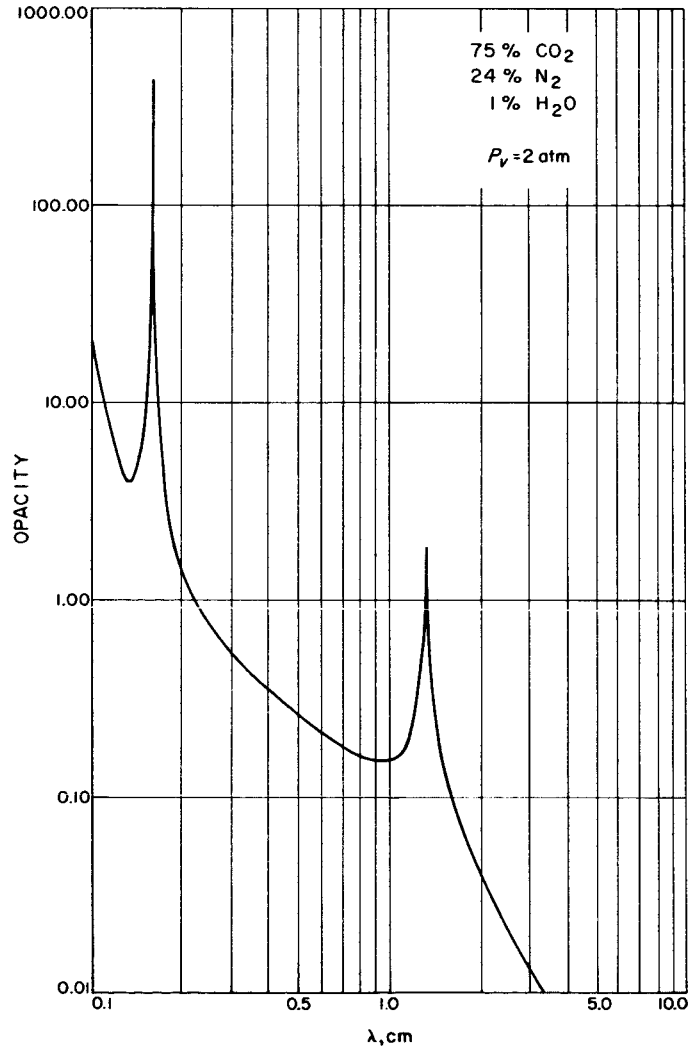


Fig. 2. The opacity normal to the surface calculated from an assumed surface pressure of 2 atm and an assumed atmosphere of 75 % CO_2 , 24 % N_2 , and 1 % H_2O

at 1.35 and 0.162 cm. The intensity of microwave radiation from the surface and atmosphere must be calculated from the solution of the equation of radiative transfer. Expressing intensity as a temperature, the intensity of a ray making an angle θ with the normal to the surface is given by

$$T(\theta) = T_s e^{-\tau_m/\mu} + \int_0^{\tau_m} T(\tau) e^{-\tau/\mu} \frac{d\tau}{\mu} \quad (\mu = \cos \theta) \quad (6)$$

where the first term is the radiation from the 580°K surface attenuated by the atmosphere and the second term is the radiation from the atmosphere itself. The complete radio brightness temperature is obtained by multiplying this expression by $\cos \theta$ and integrating for all values of θ between 0 and π .

$$T_b = 2T_s \int_0^1 e^{-\tau_m/\mu} \mu d\mu + 2 \int_0^1 \int_0^{\tau_m} T(\tau) e^{-\tau/\mu} d\tau d\mu \quad (7)$$

Numerical integration of Eq. (7) yields the desired theoretical expression for the radio brightness temperature as a function of frequency and the parameters of the Cytherean atmosphere appropriate to the planetary surface. In particular, the result of Eq. (7) may be compared with the observed values to estimate the value of pressure at the surface of Venus. This comparison is made in Fig. 3 for a set of parameters of the model atmosphere. The value of the surface pressure required to match the existing radio data is higher than one might expect on the basis of the measurements of the abundance of CO_2 above the clouds, but neither estimate of the surface pressure can claim any high degree of certainty at this

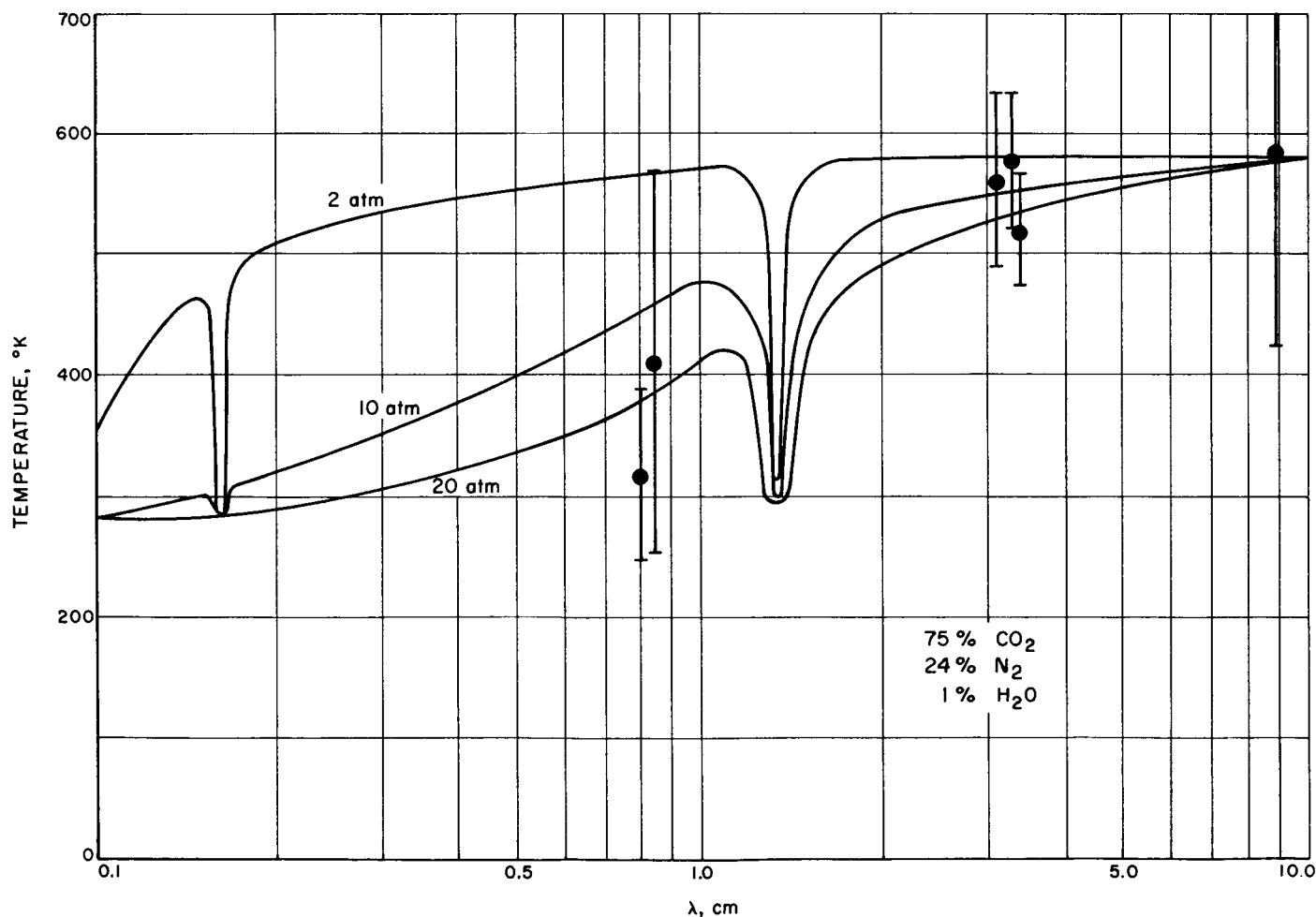


Fig. 3. The theoretical microwave spectrum of Venus for various values of the surface pressure

time. It seems fairly certain, however, that the Cytherean surface pressure is at least 4 times the terrestrial pressure and possibly as much as 30 times.

It should be emphasized that if the cm radio radiation has its origin at the surface of Venus, then radio data at a number of different mm wavelengths can be of value in determining otherwise inaccessible meteorological parameters of the lower atmosphere. This can be seen most easily from Fig. 4, where a computed radio spectrum is broken down into the contributions from various spatially different regions. Notice that the mm wavelengths have their origin in the lower atmosphere, beneath the clouds, and that this region is inaccessible to study by other means.

In the above analysis of the radio data involving a model atmosphere, no account has been taken of the attenuation of microwaves by the clouds; this may be the

reason for the discrepancy between the surface pressures computed from the radio and CO_2 data. There can be no doubt that the clouds play a predominant role in the absorption of infrared radiation and shorter wavelengths, and it is important to inquire into the absorption which they might cause in the microwave range. This problem is not easy to solve, for the very nature of the clouds has been the subject of much scientific debate for years (Ref. 20, 23-25). It is not yet clear whether the clouds are composed of liquid droplets or solid particles, nor has it been proven that the clouds are composed of H_2O or some other material. For these reasons it is difficult to be very quantitative about the possible effects of the Cytherean clouds. Certain general remarks can be made, however, and then the possible effects of clouds of H_2O vapor and ice crystals can be considered.

The particles composing the clouds will, in general, scatter and absorb (and emit) microwave radiation.

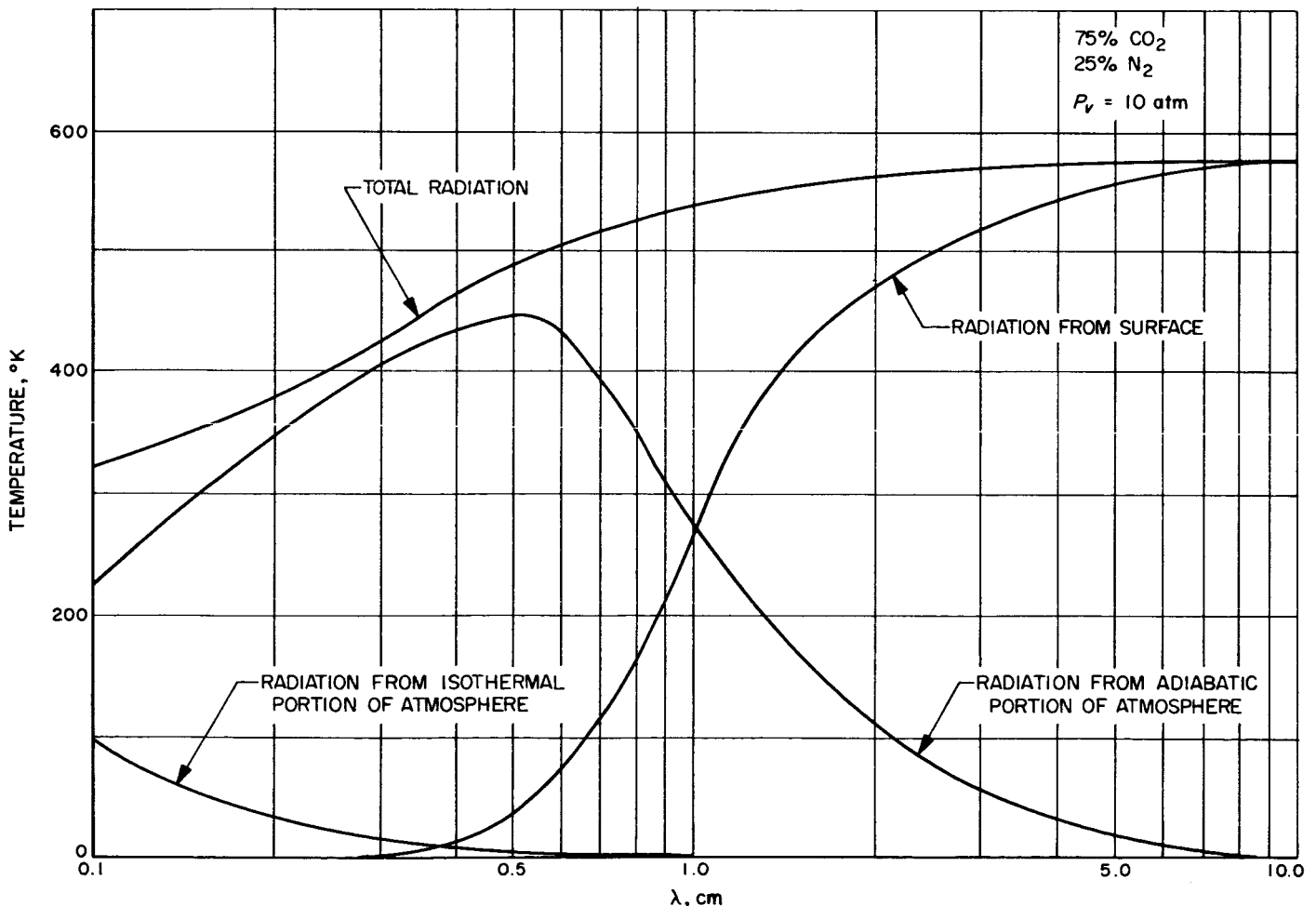


Fig. 4. Contributions from the surface and atmosphere to the total microwave radiation from Venus

However, the efficiency of the particles for these processes will depend on the wavelength, the size of the particles, and the electric properties of the particles. For spherical droplets, the scattering cross section σ_s is proportional to

$$\sigma_s \sim \lambda^2 \left(\frac{2\pi a}{\lambda} \right)^6 \quad (8)$$

while the absorption cross section σ_a is proportional to

$$\sigma_a \sim \lambda^2 \left(\frac{2\pi a}{\lambda} \right)^3 \quad (9)$$

The scattering cross section varies as $1/\lambda^4$ as it must for Rayleigh scattering. It can be seen from these equations that as long as $(2\pi a/\lambda) < 1$ the loss of energy due to scattering will be small compared to absorption. For all wavelengths and droplet sizes considered here, that condition will be met. From observations of the polarization of the reflected light from Venus it is concluded that the size of the droplets is less than 0.001 cm; thus, even for a wavelength of 0.1 cm—the shortest wavelength of interest in this report—we have $(2\pi a/\lambda) = 0.063$. Hence it can be concluded that scattering of microwaves by the clouds may be neglected in comparison with absorption.

The absorption cross section may be formally related to the usual absorption coefficient (absorption per unit length) α and the total opacity τ by the equations

$$\alpha = \int_0^\infty \sigma_a(a, \lambda) n(a) da \quad (10)$$

$$\tau = \int \alpha dl \quad (11)$$

where l is the path length and $n(a)da$ is the number of particles per unit volume with radius a in range da . To calculate the absorption cross section, use must be made of the electromagnetic theory of the interaction of electric and magnetic waves with the particles. This is a difficult problem and can be solved in closed form for only the simplest geometrical shapes. For our purposes we will use the results for spherical particles and will continue to adhere to the assumption that the particle size is small with respect to the wavelength. Under these conditions it may be shown (Ref. 26) that the absorption cross section σ_a is given by

$$\sigma_a = \frac{4\pi^2}{\lambda} a^3 \beta \quad (12)$$

$$\beta = \frac{6\epsilon_2}{(\epsilon_1 + 2)^2 + \epsilon_2^2} \quad (13)$$

where ϵ_1 and ϵ_2 are the real and imaginary components of the complex dielectric constant; i.e., $\epsilon = \epsilon_1 - i\epsilon_2$. At this point it can easily be seen from Eq. (10) and (13) that any quantitative estimates of the attenuation by the clouds can only be made after the electrical properties of the particles and their distribution in sizes is known.

Microwave attenuation in H_2O clouds, fog, and droplets has been studied extensively both theoretically (within the framework of the discussion given here) and experimentally, and it will be instructive to consider the consequences of H_2O clouds on the microwave radiation from Venus. We will ignore the possibility of actual rainfall, and consider only liquid water as it exists in clouds. It has been found empirically (Ref. 26) that the attenuation for very small droplets can be represented by

$$\gamma = \frac{0.44 M}{\lambda^2} \text{ db/km} \quad (14)$$

where M is the total liquid water content of the cloud in gm/m^3 . A slightly different expression has been obtained more recently and is plotted in Fig. 5 (Ref. 27). The principal difference between Eq. (14) and Fig. 5 is that the dependence on wavelength in Fig. 5 is not quite λ^{-2} . Use of these curves requires a knowledge of the liquid water density M in a typical Cytherean cloud. Needless to say, there are no data available on this point; only comparisons with terrestrial cloud values are available. A typical liquid water density might be 0.2 gm/m^3 (Ref. 28, Chapter 6, Section 3) in a terrestrial cloud, although the total water content (liquid, vapor, and solid) will be much higher. If the total cloud thickness is taken to be 5 km, then it can be seen from Fig. 5 that the attenuation due to the liquid water in the cloud is 0.4 db at 3 cm, 0.5 db at 1 cm, and 0.87 db at 0.8 cm wavelength. Thus the cloud would attenuate 0.8 cm radiation by about 18% and would have a negligible effect at 3 cm. On the other hand, such a cloud would drastically affect radiation at 0.4 cm, the attenuation being about 4.5 db or equivalent to an attenuation of 65%.

The presence of liquid water clouds on Venus could explain, at least in part, the lower brightness temperatures determined from the 0.8-cm data as compared to the 3- and 10-cm observations. This would help reduce the value of the surface pressure deduced from radio observations (Ref. 19), as outlined above. Very few conclusions can be drawn at the present time because of lack of data. In this connection, Fig. 5 has been computed for

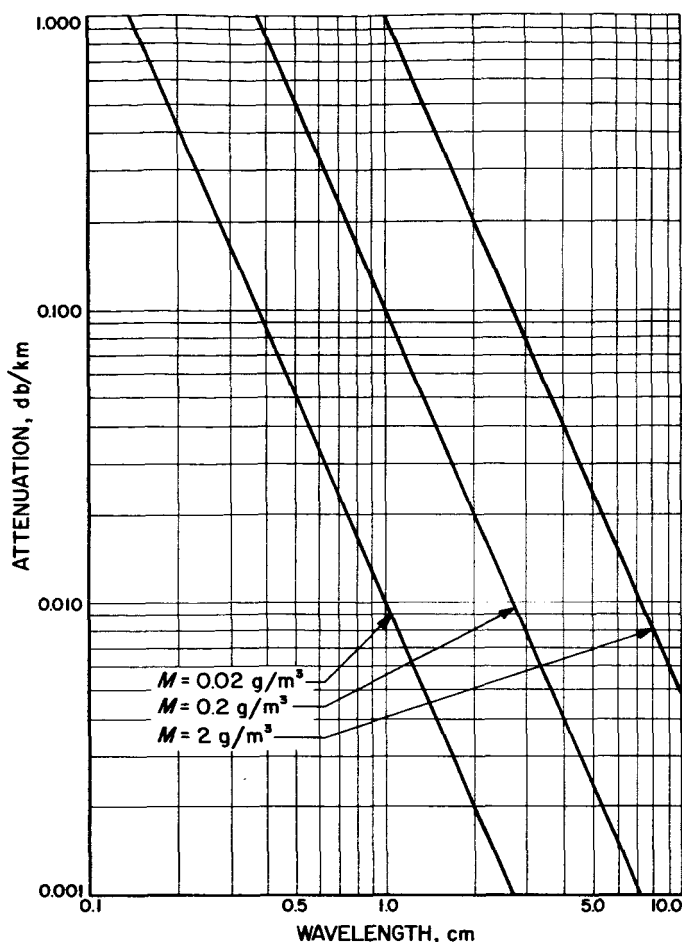


Fig. 5. Attenuation, one way, in db/km vs wavelength for various values of liquid water density in clouds

295°K; the absorption in the clouds will vary in an inverse manner with temperature, although not rapidly. The true cloud attenuation, and consequently the reradiation, should be integrated throughout the cloud thickness, but this requires a detailed model of a Cytherean cloud.

The consequences of existing and future radio measurements of Venus as a function of phase are discussed in detail in Section IV with regard to the surface temperature distribution, rotation, etc. It is appropriate, however, to attempt to ascertain whether any phase effect can be expected as a result of differing cloud conditions on the illuminated and dark portions of Venus. Again, recourse must be made to comparisons with the terrestrial case, as data are lacking for any other approach. Even on Earth, very little information is available concerning the diurnal changes in clouds, especially as relating to their liquid water content, height, and thickness. It is well known that the cloud cover is generally less at night (Ref. 28, Ch. 7) but complete cloud cover over any particular spot

on Earth does not show a strong diurnal variation, i.e., complete cloud cover is as apt to occur at night as during the day. Since Venus has a very complete cloud cover, with few if any breaks, it might be expected that the phase effect due to the clouds would be small. Possible support for this viewpoint comes from the equality of the infrared observations of the radiation from the illuminated and dark cloud layers (Ref. 1, 2). Furthermore, markings on the visible planetary surface and temporal changes in the CO_2 spectra indicate a rather high degree of turbulence, so there may be considerable interhemispherical mixing which would tend to smooth out any phase variation in the upper atmosphere. Perhaps one of the best ways to get data on this question will be by extended measurements in the mm region. As indicated above, the clouds will exhibit their main effect for wavelengths less than 1 cm and preferably near 4 mm or shorter.

Many of the problems associated with the interpretation of the radio results from Venus can be clarified by detailed measurements of the microwave radiation from a probe passing close to Venus. In addition, it can be hoped that an abundance of new information can be gained which can be related to the physics and meteorology of the planet. Radiometers are to be flown in the *Mariner* (Venus) flyby mission which operate on wavelengths chosen to yield information on the origin of the radiation and to probe the atmosphere of the planet. The wavelengths chosen are 1.9 cm, 1.35 cm, 8 mm, and 4 mm.

If the radiation originates from the solid surface of the planet, the 1.9-cm radiometer should, within the limitations of its antenna pattern, be able to measure the thermal distribution over the surface. The beamwidth is about 2 deg, which will correspond to about 550 km on the surface for a miss-distance of 15,000 km. Thus a fairly detailed map of the surface thermal distribution should be obtainable.

The radiometer, tuned to a wavelength of 1.35 cm, will measure the effect of H_2O on the microwave properties of the atmosphere. This wavelength corresponds to that of the H_2O resonance line, and the temperature as determined from the output of this radiometer should be quite different from that of the surface if H_2O is present in the Cytherean atmosphere in an abundance resembling that on Earth. Such an abundance seems indicated by high-altitude balloon observations.² In addition, as the radiometer antenna is scanned across the surface of the planet, the antenna beam will be looking through varying

²Private communication from J. Strong.

amounts of the atmosphere. Thus one should be able to correlate the output with the vertical distribution of H_2O in the atmosphere. In the event that the H_2O is not uniformly distributed in the atmosphere, the 1.35-cm radiometer output will show fluctuations from this cause whereas the other radiometers will not.

The 8- and 4-mm radiometers will give information on conditions in the atmosphere of Venus, assuming that the microwave radiation in the cm range originates from the surface. This can be seen from the curves of Fig. 4. Another probability is that the mm radiometers (especially the 4-mm radiometer) will give information about the cloud structure. From Fig. 5 note that if the clouds are composed of water droplets the 4-mm radiation will be seriously attenuated, whereas the 8-mm radiation will be less attenuated and the 1.9-cm radiometer will be affected by only the thickest of clouds. Thus, it may be possible to get a good idea of the completeness of the cloud cover and of the fine structure within the clouds. By correlating the various radiometer outputs it could be possible to separate the cloud attenuation from the atmospheric attenuation.

It is difficult to predict the amount of information to be gained from the microwave radiometric experiment, but there is no doubt that the interpretation of the data will depend to a large extent on the changes of output level of the radiometers relative to each other. This level change comes about because it can be expected that the radiation will originate from different levels in the atmosphere, no matter which of the interpretations presented above is correct. Thus it may be possible to ascertain the effects of different emissivities of surface material over rather localized areas, storms (including regions of anomalous concentrations of H_2O), and varying cloud cover. The information gained by this experiment will be greatly enhanced if the area covered on the surface by the antenna beams is increased without losing angular resolution, i.e., without increasing the antenna beamwidth. This area increase can only be accomplished by scanning the antenna as the vehicle passes by the planet.

An obvious example of the advantages of increasing the coverage of the planet is the possibility of determining the temperature distribution over the planet surface in some detail. This temperature determination will have a direct bearing on the problems of rotation rate and inclination of the axis of rotation and the thermodynamics of the surface and atmosphere combined. All these parameters are presently unknown, and yet they are of fundamental importance to our knowledge of Venus and

to the future planning of space experiments. A tremendous amount of information would be lost if all the antenna beams were bore-sighted on the center of the planet; in fact, one could then question the value of the entire experiment. On the other hand, if a scan in one dimension is made by all antennas, it then becomes possible to separate the effects of the atmosphere in attenuating the radiation from the surface and to evaluate the contribution from the atmospheric gases themselves. If the atmospheric attenuation is large, as it is likely to be at some wavelength, antenna scanning will illustrate this by means of the "limb darkening" phenomenon. Thus, near the edge—or limb—of the planet the absorption by the gases will be high and the radiometer outputs will diminish in a manner which can be related to the abundances, temperatures, and pressures of the gases. With a two-dimensional scan, one is able to determine the longitude and latitude dependence of the surface temperature. Thus when the radiometer outputs are correlated with the positions of the antenna beams relative to the terminator, it becomes possible to draw conclusions about the inclination of the axis of rotation. Further information will come from comparing the temperatures measured on the illuminated and dark portions of the planet. This temperature difference, if any, will be related to the rotation rate and interhemispherical mixing of the lower atmosphere between the two sides of Venus.

B. Dense Ionosphere

As an alternate explanation to the observed data, one can assume that the observed radiation arises from free-free transitions from thermal electrons in a highly ionized layer or ionosphere (Ref. 16-18). For such a model the brightness temperature T_i is given by

$$T_i = \int_0^{\tau_m} e^{-\tau} T(\tau) d\tau \quad (15)$$

where the opacity τ is given by

$$\tau = \int_0^z K dl \quad (16)$$

and the attenuation constant K (Ref. 29) is given by (for $z = 1$, $n_e = n_i$)

$$K = \frac{1.98 \times 10^{-23} g \lambda^2 n_e^2}{T_e^{3/2}} \quad (17)$$

with

- n_e = density of electrons in cm^{-3}
- n_i = density of ions in cm^{-3}
- λ = the wavelength
- T_e = the electron temperature
- g = gaunt factor

Absorption caused by collisions between charged and neutral particles has been neglected because it is assumed that the ionized layer is at a fairly high altitude and that the number density of neutral particles is low enough to allow the recombination coefficient to approach the value appropriate to radiative recombination ($\alpha \sim 10^{-12}$). If it is assumed that the effective temperature of the surface at the wavelength λ is T_s , then the resultant T_b as seen from above the ionosphere will be

$$T_b = \int_0^{\tau_m} e^{-\tau} T_e(\tau) d\tau + T_s e^{-\tau_m} \quad (18)$$

(The component of T_i that is reflected from the surface is neglected.)

For the simple case of a plane isothermal ionized layer we have

$$T_b = T_e \left[1 - e^{-\tau_m} \right] + T_s e^{-\tau_m}$$

Using a value for g of approximately 4, it is found that a good fit to the experimental data is obtained if it is assumed that $T_e \sim 600^\circ\text{K}$, $\int n_e^2 dl \sim 4 \times 10^{25} \text{ cm}^{-5}$, and $T_s \sim 240^\circ\text{K}$ (Fig. 6), although one can still stay within the experimental error if appropriate combinations of values of T_s from 240 to 375°K and of $\int n_e^2 dl$ from 1 to $10 \times 10^{25} \text{ cm}^{-5}$ are used. The relative percentage contribution to T_b by the surface and the ionosphere as a function of λ for this model is indicated in Fig. 7. It is to be noted that no assumption is made here regarding the electron distribution with height, and hence the effect of such an ionosphere upon a radar signal is left an open question. Also, the enhancing effect of limb brightening has been neglected.

It would be expected that if the ionized layer thickness is of the order of 100 km or so, it generally would not be isothermal. For this case, the brightness temperature is given by

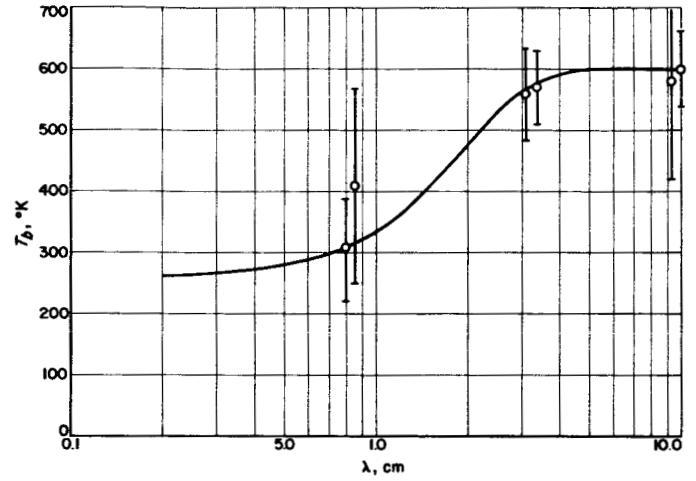


Fig. 6. Ionospheric model (isothermal)—

$$T_b \text{ vs } \lambda \text{ for } \int n_e^2 dl \sim 4 \times 10^{25} \text{ cm}^{-5}$$

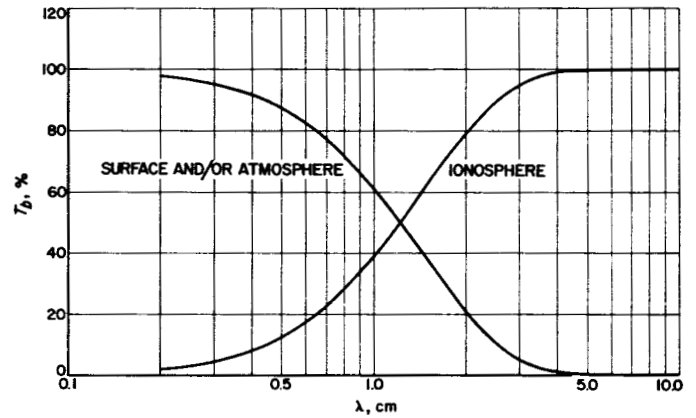
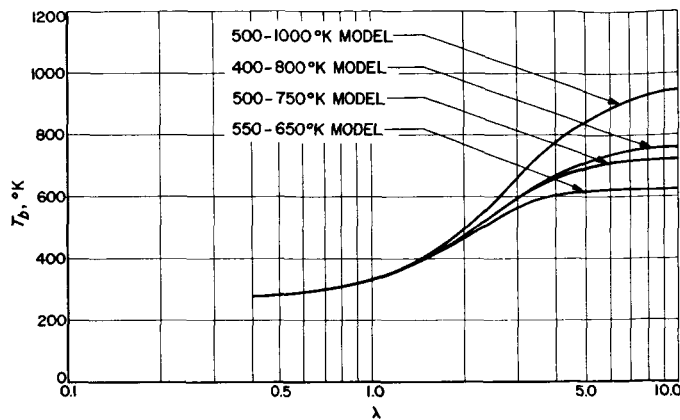


Fig. 7. Contributions from the surface and ionosphere to the total microwave radiation from Venus

$$T_b = \sum_{i=1}^n (1 - e^{-k_i \Delta l_i}) T_e(l_i) e^{-\sum_{j=i+1}^n k_j \Delta l_j} + T_s e^{-\sum_{i=1}^n k_i \Delta l_i}$$

where k_i is the average attenuation coefficient exhibited by a layer of thickness Δl_i . If it is assumed that the electron density is constant ($\sim 2 \times 10^9 \text{ cm}^{-3}$) and that the electron temperature varies linearly with height throughout the layer, it is found that the layer must be fairly close to isothermal, as seen in Fig. 8.

There are some very interesting phenomena which a model of this type will predict. For example, if the man-

Fig. 8. Nonisothermal model— T_b vs λ

ner in which the electron density varies on Earth is considered as a function of zenith angle ϕ , a rather interesting prediction is obtained involving the phase angle ψ dependence (angle between the Sun and Earth as seen from Venus) of the brightness temperature at the various wavelengths at and near the transition wavelength of 8 mm (the point between optically thick and thin regions of the assumed ionosphere). If it is assumed that the electron density dependence of zenith angle (model I) is $\alpha \cos^{1/2} \phi$, and that the observed brightness distribution is an average over the entire disk, the phase dependence of T_b is approximately given by

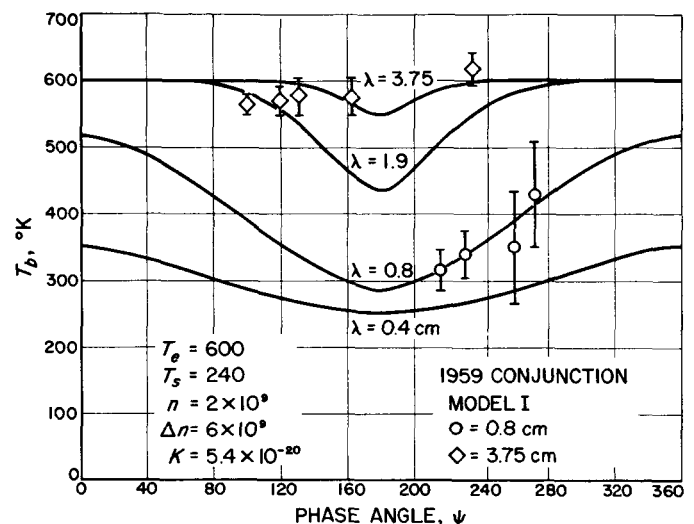
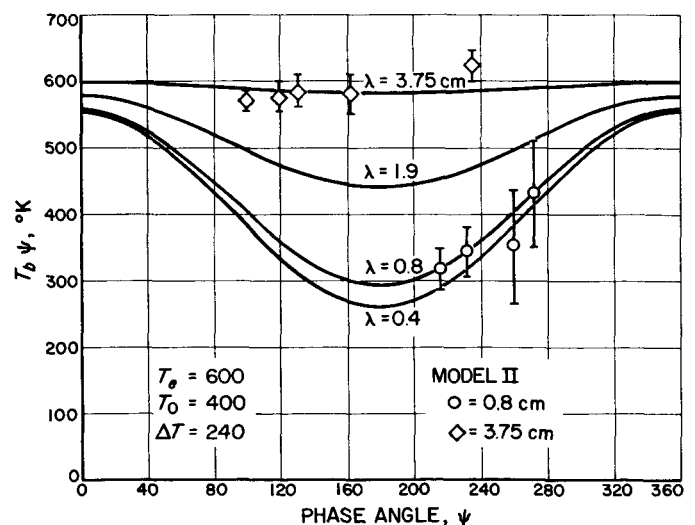
$$T_b(\psi) \sim \frac{T_s - T_e}{\pi} \left[\int_{\psi - \pi/2}^{\pi/2} e^{-k(n + \Delta n \cos^{1/2} \phi)^2} d\phi + \psi e^{-kn^2} \right] + T_e$$

where $k \sim 5 \times 10^{-20}$. If one attempts to fit the 3.75-cm and 8-mm 1959 data, some degree of success is obtained if $\Delta n \sim 4n$, where $n \sim 2 \times 10^9 \text{ cm}^{-3}$ (the layer thickness is assumed to be $\sim 100 \text{ km}$) and $T_s \sim 240^\circ \text{K}$. In the case of the F layer of the terrestrial ionosphere $\Delta n \sim 5n$. One can obviously argue that a straight line can be drawn through the 8-mm data, although Kuzmin and Salomonovich feel that the phase angle dependence is real.

A second model can be assumed in which the ionized layer is essentially uniformly spread around the planet (ionospheric winds, restriction caused by magnetic field now removed) and the phase dependence is due to a slowly rotating panel, the surface heating to a high value on the sunlit side. For this model it is assumed that

$$T_b(\psi) = T_e (1 - e^{-\tau_m}) + (T_0 + \frac{\Delta T}{2} \cos \psi) e^{-\tau_m}$$

and that the surface temperature varies as the cosine of the zenith angle, or $T_s = T_0 + \Delta T \cos \phi$. A fair fit to the data is obtained if $T_0 \sim 400^\circ \text{K}$, $\Delta T \sim 240^\circ \text{K}$. In Fig. 9 and 10 the resultant curves are plotted for the two models, with the predicted phase curves for the wavelengths of 4, 8, 19, and 37.5 mm. It is interesting to note that if sufficiently accurate data were taken near conjunction at around 20 mm or at large phase angles at around 4 mm, it might be possible to decide if either of these models exists. Unfortunately, there is no antenna in existence of sufficient size capable of operating at 4 mm.

Fig. 9. Variation in T_b with phase angle as seen from Earth for constant T_s , variable n_e Fig. 10. Variation in T_b with phase angle as seen from Earth for constant n_e , variable T_s

It is interesting to note that the terrestrial data could also fit if it is assumed that the rate of recombination is such that the electron density is appreciably lower at the anti-subsolar point of the planet.³ (One would perhaps expect this if the ionization were due to high-energy particles from the Sun; this is discussed later.) In this case, the electron temperature would have to be higher (depending upon the assumed surface temperature) and the factor $\int n_e^2 dl$ slightly higher. One can compute the extent to which the region of ionization must extend around to the dark side in order to give an integrated brightness temperature over the dark side of 600°K. One finds that for this third model roughly 40% or so of the disc at conjunction could be essentially devoid of ionization and still fit the data. At a phase angle of 90 deg the integrated temperature (at wavelengths where we are at saturation) would probably be $\geq 625^\circ\text{K}$. If the electron density were relatively uniform over the sunlit side, then one might expect that the variation in T_b with phase angle at shorter wavelengths would not be so marked. Of course, if the density does increase to a maximum at local noon, then one might expect the variation with phase at wavelengths in the transition region to be more pronounced as compared with saturation wavelengths. For such a model, one might expect greater temperature fluctuations to occur prior to or after conjunction when one is seeing primarily the dense ionization.

It is readily apparent that such a high ionized layer cannot be sustained by electromagnetic radiation alone. If the magnetic field were removed from the planet and the atmosphere were no longer shielded from high-energy charged particles, collisions between these particles and atmospheric atoms and molecules might be the sustaining mechanism for the required ionized layer. A rough idea as to the number density and velocity of particles needed can be obtained by merely equating the number of electrons produced per cm^2 per sec to the number of recombination per cm^2 per sec, or

$$\alpha \int n_e^2 dl = \frac{Nmv^3}{2V}$$

where α is the recombination coefficient, N , m , and v the number density, mass, and velocity of the impinging charged particles, and V the ionization energy for the atom or molecule being ionized. If a value for $\int n_e^2 dl$ of $\sim 10^{25}$, $V \sim 15$ ev, $\alpha \sim 10^{-12}$ is used, we see that Nmv^3

~ 480 erg/ cm^2 sec. If a number density of $\sim 10^3/\text{cm}^3$ is assumed, then a velocity of 600 to 700 km/sec is required (for protons). It is interesting to note that this is roughly the order of magnitude for N and v of the solar wind as postulated by Biermann (Ref. 30) in connection with comet tails. Also, if a number density of $\sim 1 \text{ cm}^{-3}$ is assumed, then a velocity of $\sim 6.5 \times 10^3$ km/sec is required—or for $N \sim 10^{-3} \text{ cm}^{-3}$, $V \sim 65 \times 10^3$ km/sec, and hence lower-energy cosmic rays appear to be a possible source of ionizing radiation. Of course, as the energy of the particle goes up, the probability of an ionizing collision will go down.

One of the biggest problems associated with this model is the required magnitude of the recombination coefficient. The value used is consistent only with a basically atomic region in the atmosphere. The effect of the electron component of the solar wind should not be overlooked here. It may be that the solar wind carries with it a means of lowering the recombination coefficient in addition to the high-energy ionizing particles. One obviously wouldn't "see" these electrons in the microwave region.

If the source of the ionizing particle radiation were the Sun, then one might expect to see some sort of correlation between measurements made of the Sun and Venus as well as some correlation with magnetic activity on Earth. This was suggested by Drake and it appears that some such correlation is indeed suggested when the 10.7-cm solar and 3.75-cm Venus data of 1959 are compared (Fig. 11).⁴ The suggested periodicity of the Venus data appears to be an average value of about 28 days, which is interesting when compared to the rotation rate of the Sun as seen from Venus, which is approximately 28.5 days. This, of course, suggests that there may be a close coupling between the Sun and Venus insofar as the centimeter brightness temperature of the latter is concerned. One would then perhaps go another step and attempt to ascertain whether there is some correlation between the average sunspot area on the Sun as viewed from Venus and the brightness temperature of the latter. The solar radiation at 10.7 cm is generally considered a good wavelength region for the former. It is apparent that such correlation would be indicated by a peak in the solar data which coincides with any peak in the Venus data that occurs near conjunction. Obviously, any peaks either side of the conjunction would quickly get out of phase because of the difference in the rotation

³W. W. Kellogg has suggested the possibility of a hole in the ionosphere on the dark side to account for the recent radar data.

⁴The 10.7-cm solar data has been furnished by A. E. Covington; the 3.75-cm Venus data has been furnished by Frank Drake.

rates of the Sun as viewed at Earth and Venus. A correlation of the correct type is suggested in Fig. 11 but it is admittedly quite weak. One should also note the fluctuations in T_b as compared to the probable error which would appear to be inconsistent with thermal radiation from a slowly rotating body.

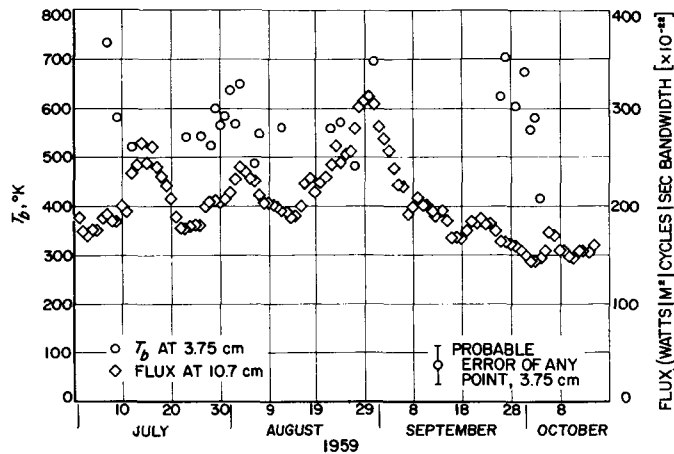


Fig. 11. Comparison of Venus 3.75-cm and solar 10.7-cm data (conjunction of 1959)

If the planet Venus were seen from a space probe with a narrow beam radiometer system in which the antenna beam was much smaller than the disc of the planet, the variation in brightness temperature with phase angle as the radiometer (angle between the Sun and the space probe as seen from Venus) passed close to the planet should be markedly different for the three models as well as for the atmospheric model. The differences between models I and II as seen by the probe radiometer at the four planned wavelengths should be readily discernible, as seen in Fig. 12 and 13. Because of the existence of the "hole" in the third model, the narrow-beam phase data should establish or reject this possibility. In the case of the atmospheric model, one would assume that the phase dependence of T_b at the shorter wavelengths would be much less than that at the longer ones.

Perhaps the most direct test for the existence of either the atmospheric or ionospheric models is the limb darkening or brightening that each would predict. The phenomenon of limb darkening has been discussed previously. Limb brightening will exist if the source of the higher temperature is the ionized layer; hence, as one scans to the limbs of the planet, at wavelengths in the transition regions there will be a temperature increase as the limbs are crossed, particularly as one crosses the sunlit limb. Of

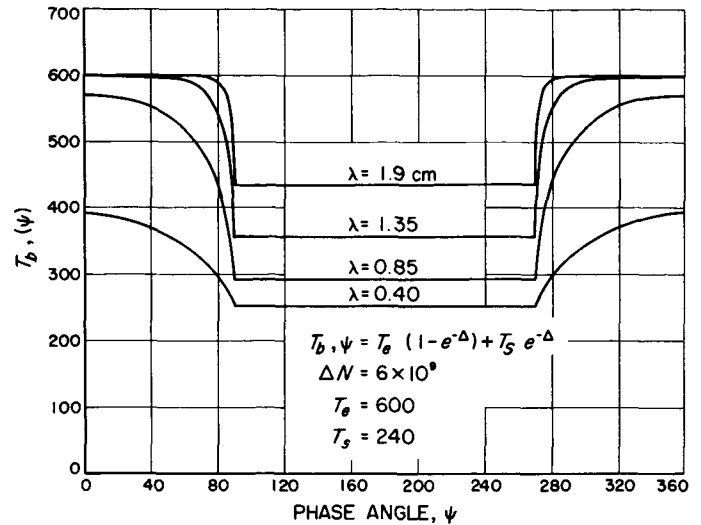


Fig. 12. Probe phase data—constant T_s , variable n_e

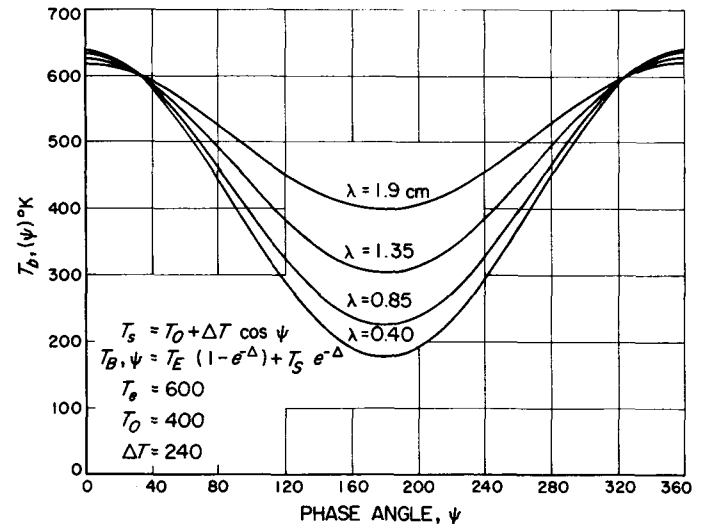


Fig. 13. Probe phase data—constant n_e , variable T_s

course, the finite beamwidth of the antenna coupled with distances to the planet associated with the probe trajectory will cause a large amount of this effect to be smoothed out. This "antenna smoothing" has been computed assuming a simple $(\sin x/x)^2$ approximation to the antenna pattern for various models, and it appears that it should be detectable. Depending upon the planet-probe distance, the curves in Fig. 14 and 15 indicate what the limb brightening data may look like. Here, $T_a(x)$ is the antenna temperature, x the distance from the center of the disc of the planet. The predicted data for $\lambda = 8$ and 13.5 mm are shown, since these wavelengths will probably show the greatest effect. A study of the relative

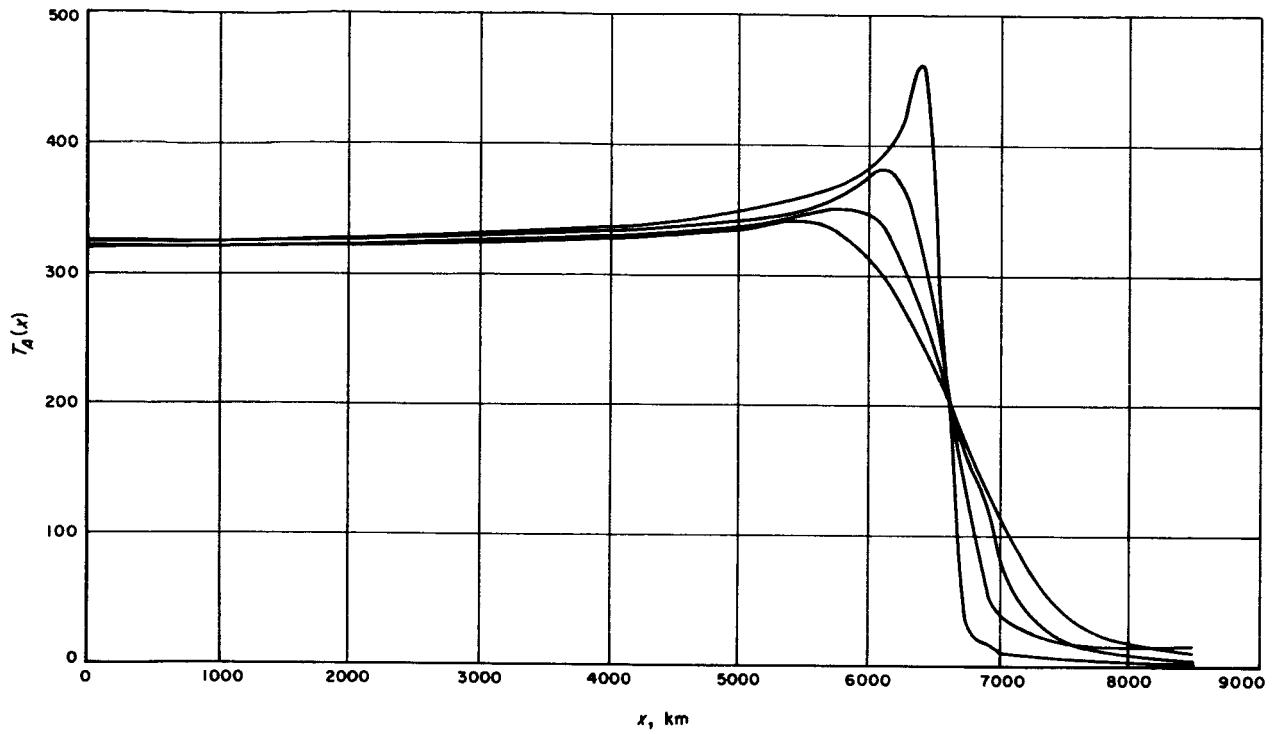


Fig. 14. 8-mm limb brightening vs miss distance

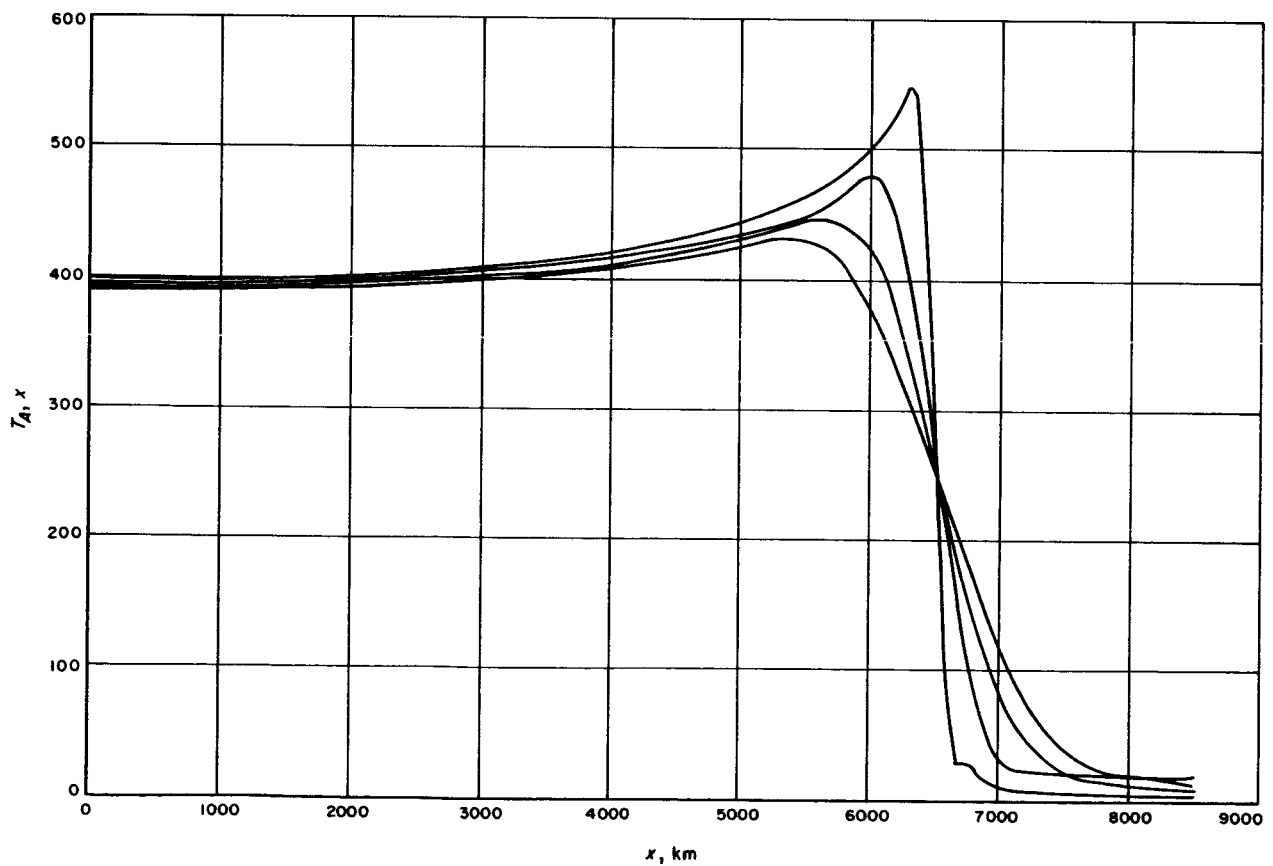


Fig. 15. 13.5-mm limb brightening vs miss distance

limb brightening observed at the several frequencies should allow an estimate of the layer thickness and shape.

Regardless of whether the particles are low-energy cosmic rays or those which come from the Sun in the form of the solar wind, the particle-ionization mechanism requires a rather low value for the Cytherean magnetic field strength ($\sim 1/30$ th that of the Earth if Biermann's estimate of the solar wind is used). Therefore, a measurement of the latter from a space probe will also be important as an indirect test for the ionospheric model. Particle measurements made near Venus will, of course, be valuable in this respect as well.

C. Atmosphere-Ionosphere Model

Since Venus is continuously covered with clouds, an obvious extension of the models is one which combines some of the features of both. In the discussion of the previous section, T_s was specified as a ground or surface temperature (referring, of course, to an equivalent depth below the surface depending upon the wavelength, surface conductivity attenuation, etc.) which was assumed essentially independent of wavelength. One should obviously not overlook the possibility that T_s refers to the equivalent temperature of Venus observed from above the cloud layer but from below the ionosphere.

The unfortunate consequences of such a model are obvious. If the properties of both the ionospheric and

atmospheric models are combined, it is possible that the surface may be "seen" thermally only over a very narrow wavelength region. The ionosphere would attenuate radiation at a wavelength longer than 8 to 10 mm, whereas the atmosphere (including clouds) would attenuate radiation at wavelengths shorter than perhaps 10 mm (up to 13.5 or 14 mm if water vapor exists below the clouds in sufficient amounts). A careful study of the data should help to establish or reject this possibility.

D. Aeolospheric Model

Opik (Ref. 31) has proposed that the surface of Venus is at 600°K and that the primary absorption of the microwave energy of less than about 1 cm wavelength is caused by a dense blanket of dust. The tremendous circulation of this dust grinds and heats the surface to the observed temperature of about 600°K . This model is apparently consistent with a large amount of the data. However, if the surface is being heated by such a mechanism, one should not expect the microwave temperature to exhibit any marked change with phase angle. The available data tend to indicate some variation in brightness temperature with phase angle, as pointed out earlier. However, the scatter in the measurements is such that this cannot be definitely established at the present time. The probe measurements, of course, will allow one to establish or reject this model because of the high precision measurements that can be made over the disc.

IV. SURFACE MAPPING AND TEMPERATURE MEASUREMENT

Radio astronomers are confronted by two fundamental problems in the course of making measurements of the radio radiation from angularly small celestial sources. It is customary to measure the received noise power from a source in terms of a temperature called the "antenna temperature" T_A , which is defined in terms of the received power by the equation

$$P_R = kT_A \Delta\nu_R \quad (19)$$

where k is the Boltzmann constant, and $\Delta\nu_R$ is the bandwidth of the radiometer. The antenna temperature is usually of the order of 10^2 to 10^4 times smaller than the receiver temperature or, in other words, the noise power from the source is 10^2 to 10^4 times less than the noise power generated in the receiver itself. The antenna temperature to be expected from a source small with respect to the antenna beam at wavelength λ can be shown as given by

$$T_A = \frac{\epsilon A_g}{\lambda^2 R^2} \int_A T(\theta, \phi) \cos \alpha dA \quad (20)$$

where ϵ is the antenna efficiency, A_g is the geometrical area of antenna aperture, R is the distance to the source, $T(\theta, \phi)$ is the temperature distribution across the source of area A , and α is the angle between the normal to the element of area dA and the direction of observation. For ground-based observations of the planets, the area A over which the integral is to be evaluated includes the entire surface visible from the Earth.

Equation (20) points up the inherent difficulties of ground-based radio astronomy and the advantages of space probe observations. First, the received power varies as R^{-2} ; hence the received radiation from a planet is many times weaker when observed from Earth compared to a radiometer-equipped probe passing close to the planet. Second, the radiation received on Earth with existing antennas is characteristic of the entire planet; i.e., it represents the integrated effect of all portions of the source visible from the Earth, and one has no unique way to get the temperature distribution across the source. To resolve any surface detail on Venus by ground-based observations at 3-cm wavelength would require an antenna of at least 1000-ft diameter, and preferably two or three times larger. On the other hand, when rather small

antennas are transported to the vicinity of Venus, the angular size of the planet is no longer very small with respect to the antenna beamwidth and Eq. (20) is no longer applicable. Under these conditions it becomes possible to measure the radiation from isolated areas of the planet and, in this way, to determine temperature differences of surface emissivity from localized areas. As an example, for a beamwidth of 2 deg, as is planned on the initial *Mariner* flight, and a miss-distance of 15,000 km, the radiometer will measure the radiation from a circular area of Venus whose diameter is about 530 km (330 miles). Thus by transporting radiometers to the vicinity of Venus it would be possible to overcome the inherent problems of ground-based observations and greatly enhance the value of the data obtained. Because the signal strength will be increased, improved accuracy will be obtained on the temperature measurements, and small portions of the planetary surface can be examined to the exclusion of other portions.

In considering the possibility of mapping the temperature distribution of Venus it is worth while to consider what type of temperature distribution might be expected, what evidence exists at the present time for any particular distribution, and what information about Venus might be deduced from a known temperature distribution. Needless to say, the temperature on the surface of the planet will be intimately connected with such fundamental properties as the rotation rate, insolation, orientation of the axis of rotation, composition of the surface, composition of the atmosphere, surface pressure, winds, surface irregularities, nature and extent of the cloud cover, etc. Since none of these quantities is directly measurable by current techniques, only very general and somewhat speculative statements can be made at this time. There seems to be little doubt that the pressure at the surface of Venus is at least as great as on the Earth, and evidence seems to suggest that there will be rather strong winds present. Thus convection can be expected to play a dominant role in determining the temperature distribution, particularly if the rotation rate is slow, i.e., slow with respect to the thermal time constant of the surface-atmosphere system. Unfortunately, the rotation rate is not known, and estimates range from 1 to 225 days, which points up the state of our knowledge of Venus. Another important factor in fixing the temperature will be the extensive cloud cover. The day-night temperature difference will be found to be less because the clouds serve as a heat reservoir and tend to warm the

planet surface at night. Even on a rapidly rotating planet such as the Earth, it is a common experience that cloudy nights are not as cold as clear nights.

Some information about the surface temperature distribution can possibly be obtained from the radio measurements made at different phase angles of Venus. The phase data currently available are lacking in several respects: (1) uncertainties in the measurements are about as large as the variation of the radio brightness temperature with phase; (2) measurements have been made only over a rather small range of phases near inferior conjunction; (3) measurements have been made by different observers at different inferior conjunctions. Nevertheless, it can be expected that all of these objections will be removed shortly, and it is of considerable advantage to learn what can be deduced from the existing data and how to interpret future data. A preliminary analysis has been made of the data in Table 2, and the potential of radio phase measurements for gaining knowledge of the Cytherean surface and rotation properties has been discussed. The method of attack and the conclusions will be outlined briefly here.

If there is a substantial temperature difference between the sunlit and dark sides of Venus, it can be expected that the intensity of the radio radiation will depend on the relative sunlit and dark areas of the planet presented to the Earth. A continuously varying function and a convenient parameter with which to compare the radio results is the ratio of sunlit area A_l to the total area A_t of the planetary disc k . Thus k varies from one to zero to one in a complete synodic period of Venus. As a first approximation it might be expected that the radio brightness temperature T_b would vary linearly with k on both sides of inferior conjunction, since average temperatures could be assumed for the light and dark sides of the surface, T_l and T_d , respectively, and could be related to the radio brightness temperature by the equations

$$T_b = T_l \frac{A_l}{A_t} + T_d \frac{A_d}{A_t}, \quad k = \frac{A_l}{A_t} \quad (21)$$

Then

$$T_b = T_l k + T_d (1 - k), \quad A_l + A_d = A_t \quad (22)$$

Equation (22) is plotted with the experimental results in Fig. 16, and it can be seen that the radio results fit the approximation to a fair degree over the range of k near inferior conjunction. However, it is to be noted that the slope prior to conjunction is very definitely less than the slope after conjunction, and this has important conse-

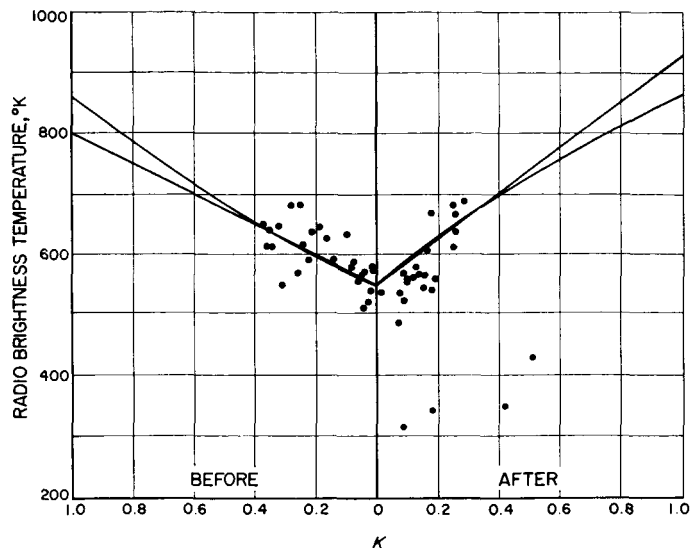


Fig. 16. Radio brightness temperature as a function of k , before and after inferior conjunction; the curved lines are plots of Eq. (22)

quences for the interpretation in terms of conditions on Venus. Furthermore, the representation given by Eq. (22) is a convenient way to present the data but offers little insight into the conditions that might exist on Venus as more realistic models of the surface temperature distribution are constructed.

To carry the interpretation of the data further, it is necessary to assume a temperature distribution on the surface and to integrate this distribution over the entire surface area accessible to the Earth according to the expression

$$T_b = \frac{1}{\pi R_v^2} \int_A T(\theta, \phi) \cos \alpha dA \quad (23)$$

where R_v is the radius of Venus and the other quantities are as previously defined. Thus one is led automatically to consider various possible models of the Cytherean surface temperature to interpret the radio phase data, and certain models can be rejected as not matching the experimental results. Furthermore, since possible models depend upon the rotation period and the inclination of the axis of rotation, it is possible to draw conclusions about these important quantities.

Suppose it is assumed that the axis of rotation has zero inclination and that the rotation period corresponds to the sidereal period; this case was referred to as "synchronously rotating" in Section II-A. Then it can be expected that the temperature will be symmetrical with

respect to the subsolar point, and a trial temperature distribution might be

$$T(\theta, \phi) = T_0 + T_1 \cos^n \theta \quad (24)$$

where θ is the angle from the subsolar point, and ϕ becomes unnecessary because the isothermal contours are concentric circles about the subsolar point. If the planet had no atmosphere, it might be expected that $n = 1/4$, corresponding to the insolation; but since convection is a very efficient means of heat transfer and since winds are very probable on Venus, there is no reason to expect that $n = 1/4$ will be a valid approximation in this case. The integration can be conveniently handled in closed form for the case $n = 1$ and will serve to bring out certain valuable conclusions. Inserting Eq. (24) in Eq. (23) and carrying out the integration gives

$$T_b = T_0 + \frac{2}{3} T_1 \cos i = (T_0 + \frac{2}{3} T_1) + \frac{4}{3} T_1 k \quad (25)$$

where i is the phase angle, defined as the angle between the Sun and the Earth as seen from Venus and taken to be between 0 and 180 deg prior to inferior conjunction and between 180 and 360 deg after conjunction. The relation between k and i is simply

$$k = \frac{1}{2} (1 + \cos i) \quad (26)$$

It can be seen from Eq. (25) that this relation will not fit the experimental data, because the slope of the T_b vs k line is the same on both sides of conjunction. Furthermore, no reasonable temperature distribution which is symmetrical about the subsolar point will give different slopes on opposite sides of conjunction; thus the radio phase data are evidence that the planet is not rotating at the sidereal rate.

Another possible temperature distribution which might be considered and which would be more applicable to a rotating planet is given in terms of the Cytherean latitude λ and longitude L , where L is measured from the subsolar meridian. One such case might be

$$T(\lambda, L) = T_0 + T_1 \cos \lambda + T_2 \cos \lambda \cos (L + \gamma) \quad (27)$$

where the second term represents the latitude variation and the third term is the day-night variation, the amplitude of which decreases with latitude. The phase lag λ is inserted to allow for the fact that the maximum temperature may not occur at noon on Venus owing to rotation of the planet. On the Earth, for example, the maximum temperature usually occurs at 3 hours past noon, corresponding to a γ of 45 deg. Using this temperature distribution and proceeding as before yields the result

$$T_b = (T_0 + \frac{8}{3\pi} T_1) + \frac{2}{3} T_2 \cos (i + \gamma) \quad (28)$$

This equation, fitted to the experimental data, is also plotted in Fig. 5 using Eq. (26) to relate i and k . In this plot the values used are

$$T_0 + \frac{8}{3\pi} T_1 = 705^\circ\text{K} \quad T_2 = 235^\circ\text{K} \quad \gamma = +7^\circ 00' \quad (29)$$

The important result in this case is that this curve fits the data near inferior conjunction as well as Eq. (22), but in addition gives different slopes on opposite sides of conjunction. This is a direct result of allowing an asymmetrical temperature distribution as represented by γ . Note also that γ turns out to be considerably smaller than the terrestrial value, which is entirely consistent with a planet rotating slowly with respect to the thermal time constant of the planetary system, i.e., surface and atmosphere. The sense of rotation is direct.

It is to be emphasized that the above calculations are intended only as a guide to the interpretation of the radio phase data. Many things have been neglected or tacitly assumed. For instance, data have been used from several conjunctions without regard to the effects of axis inclination, obliquity of the orbit of Venus, or the wavelength of the radio observations. In particular, the measurements at 8 mm also show a phase dependence similar to that at 3 and 10 cm, but there are insufficient data to carry out an analysis as above. More complete data are needed before the effects of these parameters can be evaluated, but it can be expected that the radio phase measurements will be extremely valuable when interpreted in terms of the physics and/or meteorology of Venus. Also, it is seen that no information can be obtained about the magnitude of the latitude dependence of the surface temperature distribution from this analysis. This situation may change when sufficient data are available to include the effect of axis inclination.

Perhaps it should be pointed out that the uncertainty which exists in the current phase data does not allow selection of any particular model of the surface temperature distribution, and this situation is not likely to change in the immediate future so long as observations are limited to those of ground-based installations. The *Mariner* radiometric experiments, on the other hand, offer an excellent opportunity to get detailed information about the surface temperature over the planet, and this information will be invaluable in determining the rotation axis,

rotation rate, thermodynamics of the atmosphere, and possibly something of the thermal coefficients of the surface material. Radio observations with a resolution of about 530 km on the surface can be made only from

stations near Venus, and it is very likely that only radio observations can give as much detail about conditions on the surface without landing instrument packages on the planet.

V. RADIOMETER SYSTEM

Radiant energy is the type of energy that travels in the form of electromagnetic waves. It has its origin in the excitation of some substances by electrical discharge, heat, or other methods. When radiation falls on a material substance, it is, in general, partly reflected, partly absorbed, and partly transmitted. A surface that absorbs all the radiation falling on it, and thus neither transmits nor reflects at all, is defined as a black-body surface. It can be shown that a black body radiates more energy in any wavelength interval per unit area per unit time than any other body at the same temperature, provided the radiation is due to temperature alone.

It can also be shown that a black body radiates a total amount of energy dependent on temperature alone, and that the energy is distributed among various wavelengths according to a definite relation called Planck's law. According to this law, the radiation from a black body of infinitesimal area dA , at absolute temperature $T^\circ\text{K}$, in a direction perpendicular to dA , is given by

$$J_\lambda = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \text{ watts/cm}^2/\text{steradian/unit wavelength} \quad (30)$$

where λ is the wavelength, and C_1 and C_2 are constants. The spectrum of this radiation extends over all wavelengths from zero to infinity.

Over wide ranges of values of wavelength, frequency, and temperature it is possible to simplify the form of Planck's law with negligible error. If the exponent in the denominator of Eq. (30) is sufficiently small, the denominator of the function becomes nearly equal to the value of the exponent itself. This simplification leads to a form of the radiation law called Rayleigh-Jeans law, which is valid in the region of interest in this report.

The Rayleigh-Jeans form of Eq. (30) is

$$J_\lambda = \frac{C_1}{C_2} \lambda^{-4} T \text{ watts/cm}^2/\text{steradian/unit wavelength} \quad (31)$$

In order for this approximation to apply with an error of less than 1%, it is sufficient that

$$\lambda T > 72 \text{ cm } ^\circ\text{K} \quad (32)$$

In the Rayleigh-Jeans area, the radiated power is proportional to the square of the frequency, the first power

of the temperature, the width of the frequency interval being considered, and the area of the emitting surface.

Electrical noise that has its origin in random fluctuations of charges in conductors is called Johnson noise. The expression for the power that originates in this manner is well known as

$$P = kT \Delta f \text{ watts} \quad (33)$$

where k is Boltzmann's constant, T is the absolute temperature, and Δf is the bandwidth. According to Eq. (31), the power radiated per unit bandwidth from a black body is also proportional to the temperature of the body. Because of this fact, it is customary in microwave radiometry to measure the power received by an antenna in units of temperature. It is in this fashion that the concept of antenna temperature arises; and it can be shown that if the average receiving aperture of an antenna is taken into consideration, the total power radiated into an antenna from a black body which is resolved by the antenna beam is given by

$$P = 2 kT \Delta f \quad (34)$$

But since the receiving system accepts only one polarization, it responds to only one-half this amount. Therefore, the power received from the black body is identical in amount and spectrum with the Johnson noise power at the same temperature. A change in temperature of the black body is entirely equivalent to a change in the internal noise level of the receiver. Therefore, antenna temperature is defined as that temperature of a matched termination replacing the antenna which produces the same noise power received by the receiving system from the antenna.

If the antenna beam does not resolve the black-body source, the antenna temperature is reduced from the source temperature by the ratio of the solid angle subtended by the source to the solid angle subtended by the entire antenna beam.

A. Radiometers

A radiometer is a device for the detection and measurement of radiant energy. In all radiometers, the most important element is the detector. In the radio wavelengths region, the detector takes the form of a crystal diode. The crystal detector is a square-law device; the output current is proportional to the input power. It is

easy to show that, for such a device, the detection or rectification efficiency is proportional to the input power. The crystal detector, therefore, performs better at high signals than at low signal levels. As a consequence of this fact, the detection of microwave radiation is usually preceded by some form of amplification. The amplification may be done at the frequency of reception, as is done with traveling-wave-tube radiometers, or at some intermediate frequency after frequency conversion, as in the case of the conventional superheterodyne radiometer. In fact, most of the weight and volume of the conventional microwave radiometer are devoted to the radio-frequency or intermediate-frequency amplifiers and their associated power supplies. If an absolute minimum of weight, volume, and power consumption is imperative, one is forced to resort to immediate detection of the signal with all amplification performed at audio frequencies. (The simple crystal set radio receiver is an example of such a receiving system.) A radiometer of this type has been called a crystal-audio radiometer by analogy with the crystal-video radar receiver which is commonly used in radar beacon service where minimum power consumption is desirable and the input signal is ample.

B. The Crystal-Audio Radiometer

A block diagram of a simple single-channel crystal-audio radiometer is shown in Fig. 17. Since the thermal signal received by the antenna has the same spectrum as the amplifier noise, it is modulated before detection in order that antenna temperature changes can be distinguished from changes in amplifier noise level. The output from the amplifier then contains in its spectrum a component whose amplitude is proportional to the input signal power because of the square-law detector and whose frequency is the same as that of the modulating signal. The phase-sensitive detector acts as a narrow-band filter to extract this component from the noise in the amplifier output and produces a dc signal which is proportional to the input signal power and, because of the

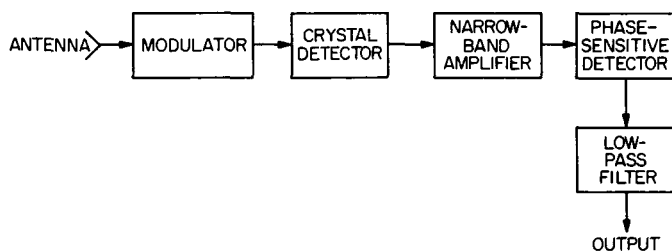


Fig. 17. Block diagram of a simple crystal audio radiometer

Rayleigh-Jeans law, proportional to the antenna temperature.

It can be shown that the change in antenna temperature which produces a change in dc output just equal to the rms noise fluctuations in the output is given by

$$\Delta T = \frac{1}{BM} (T_0/k\tau)^{1/2} \quad (35)$$

where

ΔT = change in antenna temperature

B = predetection bandwidth

M = crystal figure of merit

T_0 = amplifier noise temperature

k = Boltzmann's constant

τ = time constant of the low-pass filter at the output of the phase-sensitive detector.

In order to make quantitative measurements of the antenna temperature, it is necessary in practice to calibrate the radiometer. This is usually done by inserting a noise signal of known equivalent temperature.

C. Multichannel Radiometer for Mariner

The objectives of the microwave program of the *Mariner* mission can best be met by the use of four radiometers operating simultaneously at four different frequencies. As presently planned, each of the four radiometers is somewhat more sophisticated than the simple one described in the preceding paragraph. Other than the necessary complications of automatic calibration, etc., the primary difference is that instead of simple on-off modulation of the signal from the antenna, provision is made to switch the detector from the antenna to a "comparison" horn feed which is pointed to cold space. Since thermal radiation from space is nearly nonexistent at the wavelengths under consideration, this procedure furnishes one calibration point at zero deg Kelvin, thereby necessitating only one other calibration point from the automatic calibration equipment.

The sensitivity criterion requires that radiometric measurements made during the flyby should yield the thermal spectrum of Venus at the four operating wavelengths to an accuracy of 10% or better of the peak amplitude. In this criterion the rms fluctuations as indicated by the

crystal video equation were not used. A more meaningful quantity is the peak-to-peak fluctuations. In an analog presentation of the data, most observers will agree that a clearly recognizable change in amplitude is one equal to the peak-to-peak fluctuations. Here, the criterion for peak to peak has arbitrarily been taken as approximately 6 times the rms fluctuations. The performance characteristics of the radiometer are given below:

Operating wavelength, mm	Tolerance, mm	Antenna beamwidth, deg
4.0	± 0.25	2.0
8.5	± 0.5	2.0
13.5	± 0.135	2.0
19.0	± 0.5	2.8

Displacement of antenna beams

off boresight	$\frac{1}{4}$ deg maximum
Maximum sidelobe level.....	-23 db
Temperature calibration	2% absolute accuracy

Receiver predetection bandwidth:

4.0 mm	6.7 Kmc
8.5 mm	3.5 Kmc
13.5 mm	1.5 Kmc
19.0 mm	1.6 Kmc

Modulator	one for each channel
Postdetection integration	≤ 20 sec

RMS temperature fluctuations at the output:

4.0 mm	$\leq 5^\circ\text{K}$
8.5 mm	$\leq 8^\circ\text{K}$
13.5 mm	$\leq 5^\circ\text{K}$
19.0 mm	$\leq 8^\circ\text{K}$

(Values indicated are maximum over a 1-hr period with an integration time of about 20 sec.)

The entire radiometer complex (including power converters) weighs about 30 lb and requires about 10 watts. The analog signal is converted to digital information with an accuracy equivalent to 9 bits.

The scan program planned for the radiometer is the same as that used for the ultraviolet spectrometer, as both are to be on the same articulating head; this is discussed in Ref. 32. Basically, it is a one-dimensional stepping scan such that the motion is in 2.4-deg steps along a line inclined 15 deg to a line through the cusps (a perpendicular to the orbital plane of Venus). The motion of the spacecraft around the planet affords the scan around the planet. The scan program includes periodic looks away from the planet into cold space for calibration purposes.

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